Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)

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Outline

- T-MATS Description
- Background
- Framework
- Block Sets
- Examples
- Conclusion
- Future work

T-MATS Description

- Toolbox for the Modeling and Analysis of Thermodynamic systems, T-MATS
  - Modular thermodynamic modeling framework
  - Designed for easy creation of custom Component Level Models (CLM)
  - Built in MATLAB®/Simulink®
- Package highlights
  - General thermodynamic simulation design framework
  - Variable input system solvers
  - Advanced turbo-machinery block sets
  - Control system block sets
- Development being led by NASA Glenn Research Center
  - Non-proprietary, free of export restrictions, and open source
    - Open collaboration environment

Background

- Thermodynamic simulation examples

Model Type	Examples
Steady-State (system convergence may be required)	Gas turbine cycle model • e.g., performance models
Dynamic with Quasi-steady-state variables (multi-iteration simulation; time and system convergence)	Gas turbine model with spool dynamics only. (real time running capability) • e.g., control models
Fully Defined Dynamic Simulation (iteration over time)	Dynamic gas turbine model with spool and volume dynamics (typically runs more slowly) • e.g., near stall performance models

Background: Industry Study

Package	User Friendly*	Flexibility*	Export Restricted	Source code available	Dynamic	Control System	Cost
C-MAPSS40k, NASA	High	Low	Yes	Yes	Yes	Yes	MATLAB
Matlab: Thermlib toolbox, Eutech	High	Medium	No	No	Yes	No	MATLAB + $4900
Cantera, Open source	Low	High	No	Yes	No	No	None
Gas Turbine Simulation Program (GSP), NRL	Medium	Medium	No	No	Yes	Yes	$4,000
GasTurb, Nrec	Medium	Low	No	No	Yes	Yes	$1340
T-MATS, NASA	High	High	No	Yes	Yes	Yes	MATLAB

Definitions:

1* User Friendly, Controls Perspective

Low : Code based

Med: Model based

High: Model based with package implemented in a platform that is an industry standard

2* Flexibility

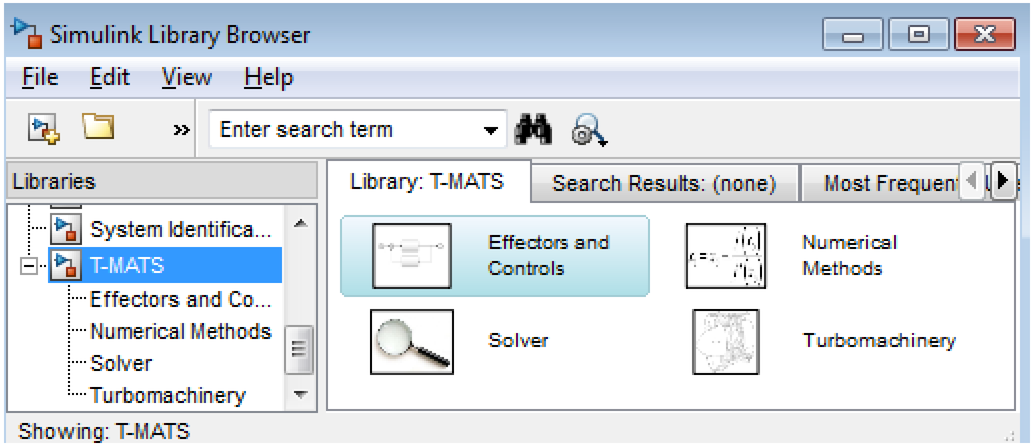
Low : Plant configuration set

Med: Object oriented, objects difficult to update

High: Object oriented, objects easily adaptable by user

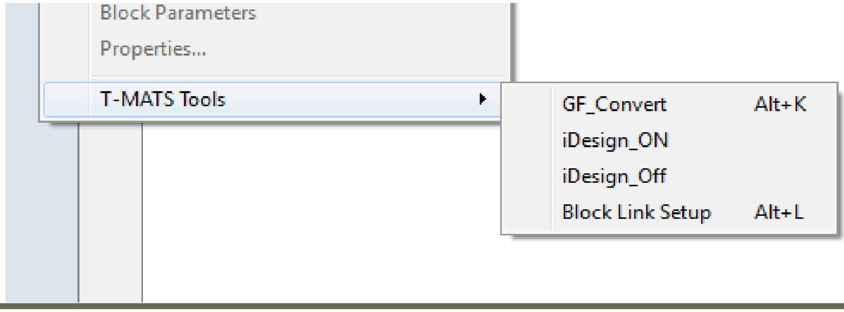
T-MATS Framework

- T-MATS is a plug-in for a MATLAB/Simulink platform
  - additional blocks in the Simulink Library Browser:



Added Simulink Thermodynamic modeling and numerical solving functionality

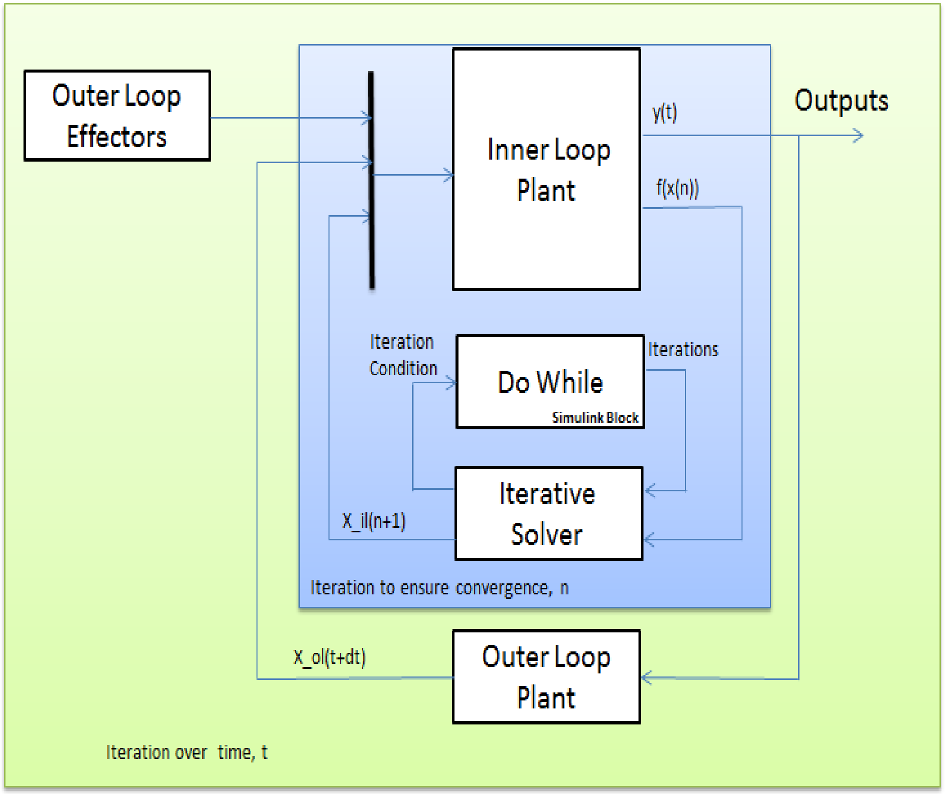
  - additional diagram tools for model development in Simulink:



Faster and easier model creation

T-MATS Framework

- Dynamic Simulation Example:
  - Multi-loop structure
    - The "outer" loop (green) iterates in the time domain
      - Not required for steady-state models
    - The "inner" loop (blue) solves for plant convergence during each time step



Blocks: Numerical Solver

- Many Thermodynamic models are partially defined and require a solver to ensure model conservation (e.g., mass, energy, etc.).
  - In many gas turbine simulations, component flow will typically be solved by an independent solver.

- T-MATS contains solvers that perform in two main steps:
  - Automated Jacobian (system gradient) Calculation

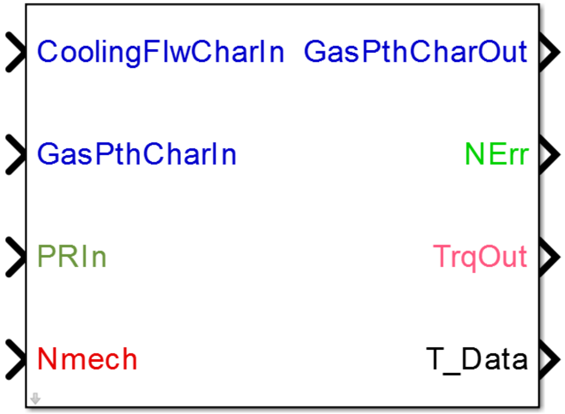
$$J = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_m}{\partial x_1} & \cdots & \frac{\partial f_m}{\partial x_n} \end{bmatrix}$$

    - Each plant input is perturbed to find the effect on each plant output.
  - Newton-Raphson method is used to “converge” the system.

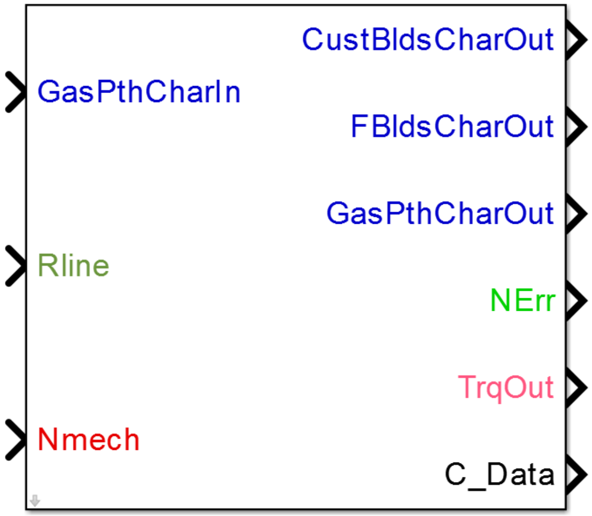
$$x(n+1) = x(n) - \frac{f(x(n))}{f'(x(n))}$$ where, $$f'x(n) = J$$

Blocks: Turbo-machinery

- T-MATS contains component blocks necessary for creation of turbo-machinery systems
  - Models based on common industry practices
    - Energy balance modeling approach
    - R-line compressor maps in Compressor model
    - Pressure Ratio maps in Turbine model
    - Single fuel assumption
    - Flow errors generated by comparing component calculated flow with component input flow
  - Includes blocks such as; compressor, turbine, nozzle, flow splitter, and valves among others.
  - Built with S-functions, utilizing compiled MEX functions



Turbine



Compressor

Blocks: Controls

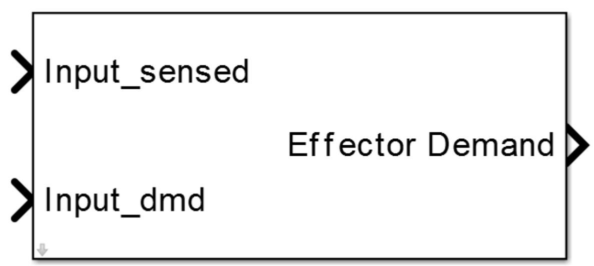
- T-MATS contains component blocks designed for fast control systems creation
  - Sensors:

1st order Sensor

  - Actuators:

1st order Actuator

  - PI controllers:

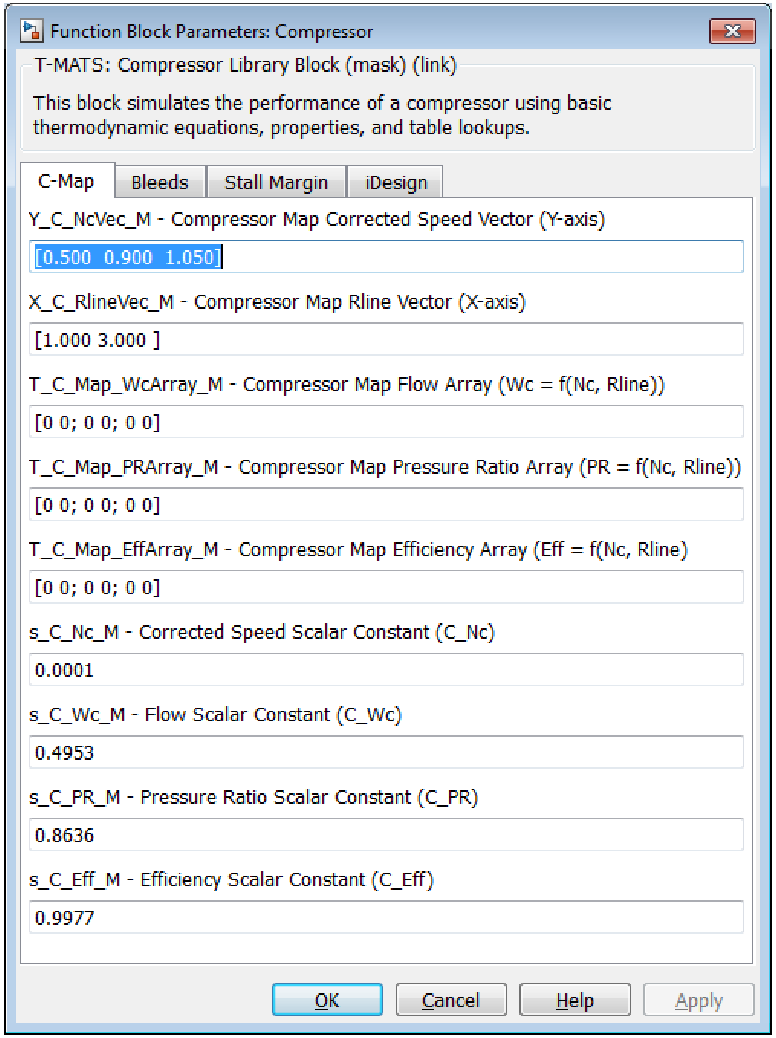


Simple PI controller

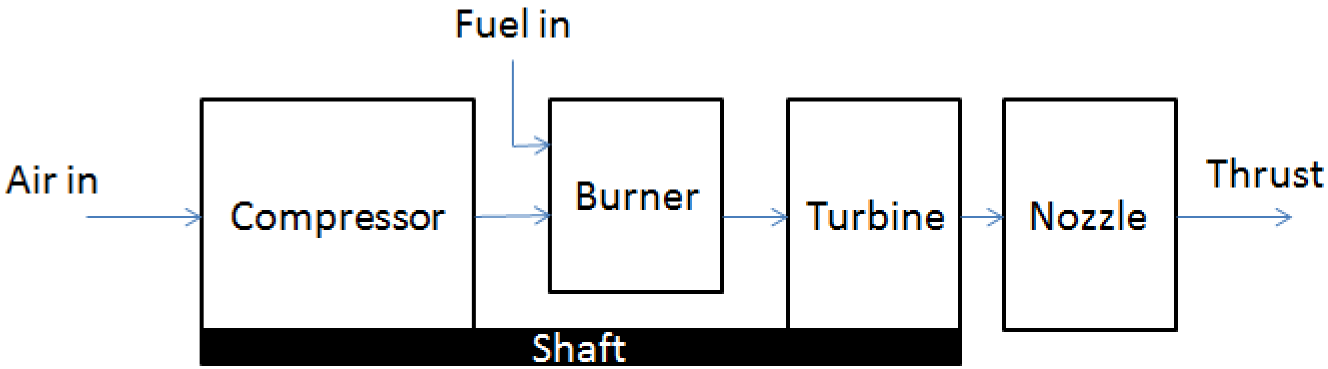
Blocks: Settings

- The T-MATS Simulation System is a highly tunable and flexible framework for Thermodynamic modeling.

  - T-MATS block Function Block Parameters
    - fast table and variable updates
  - Open source code
    - flexibility in component composition, as equations can be updated to meet system design
  - MATLAB/Simulink development environment
    - user-friendly, powerful, and versatile operation platform for model design

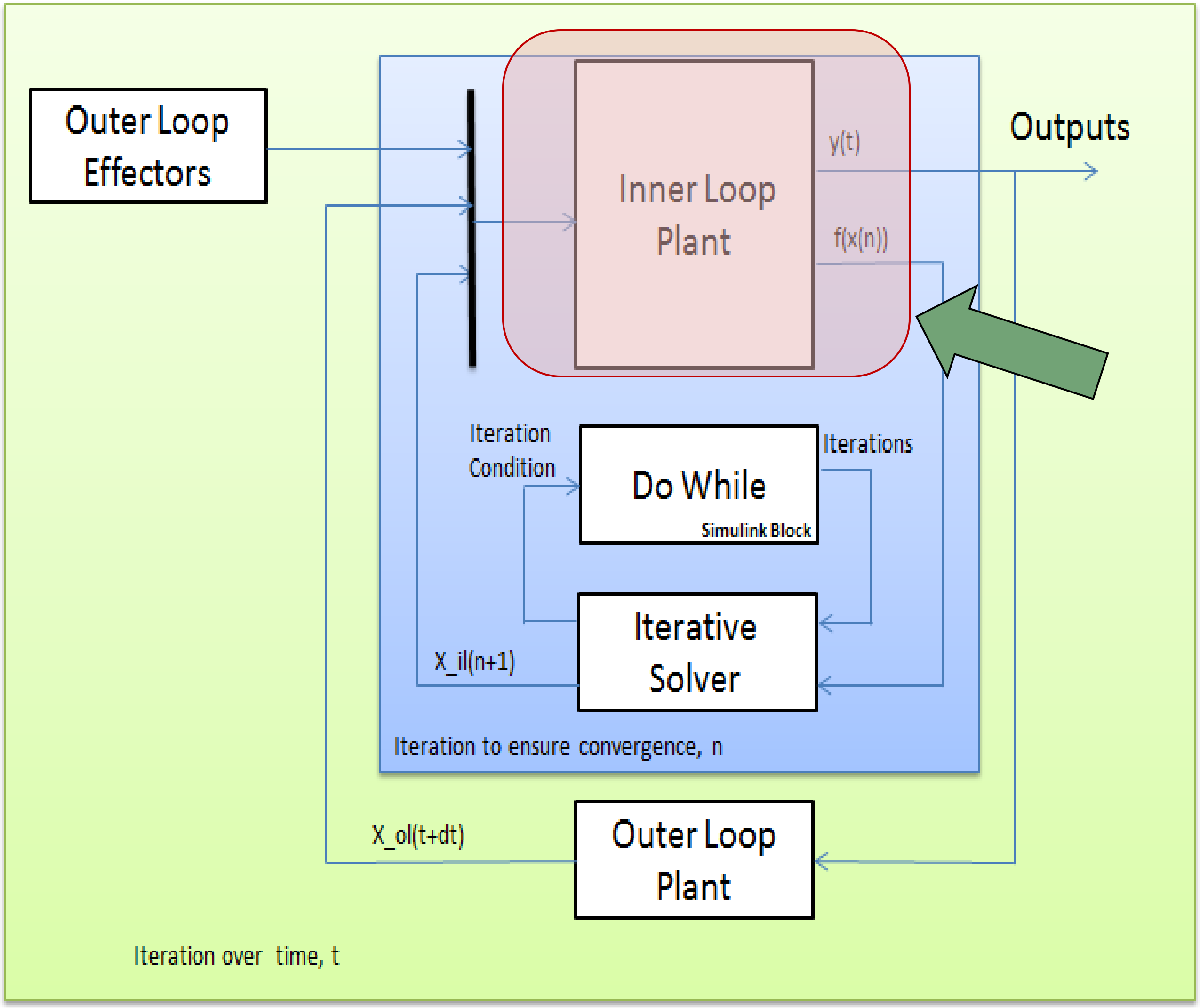


Dynamic Gas Turbine Example: Objective System

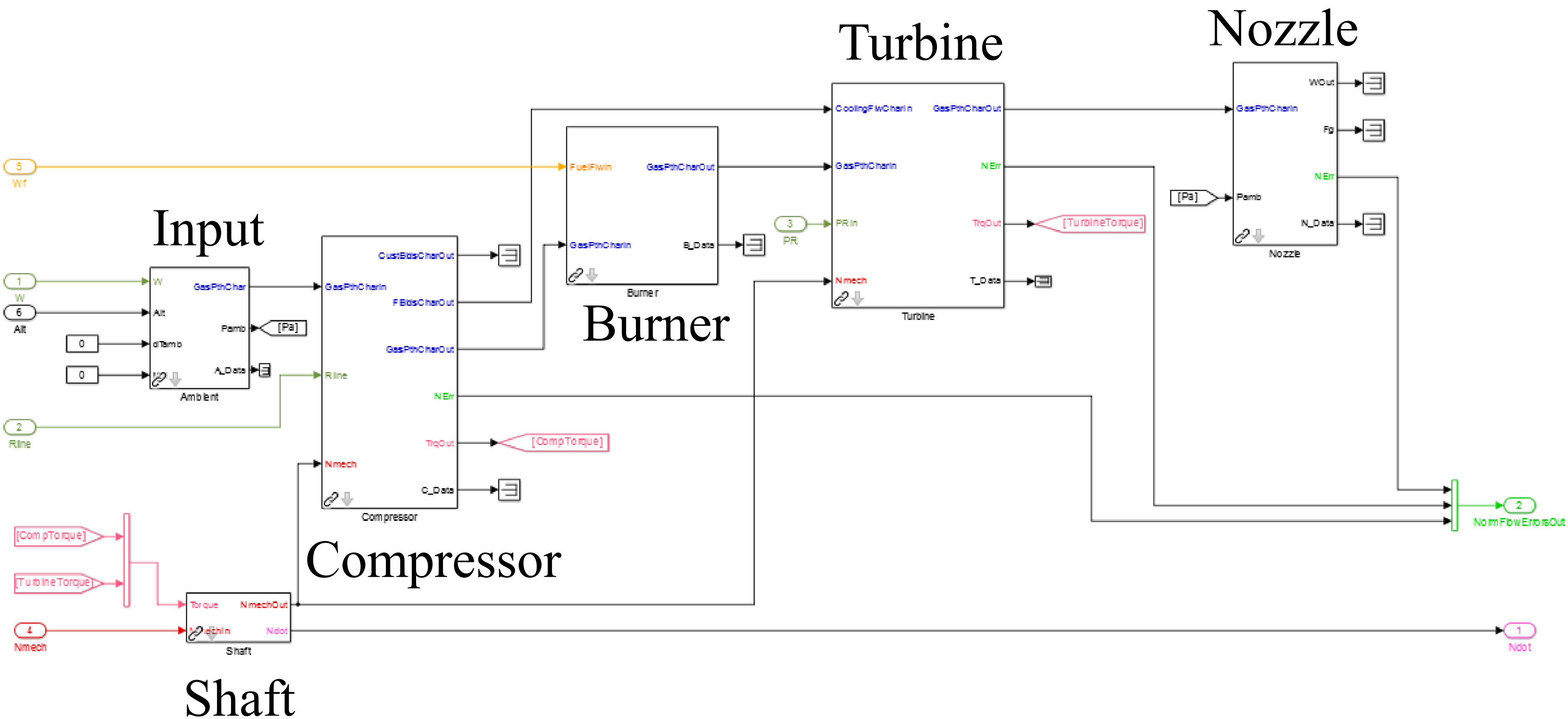


Simple Turbojet

Dynamic Gas Turbine Example: Creating the Inner Loop

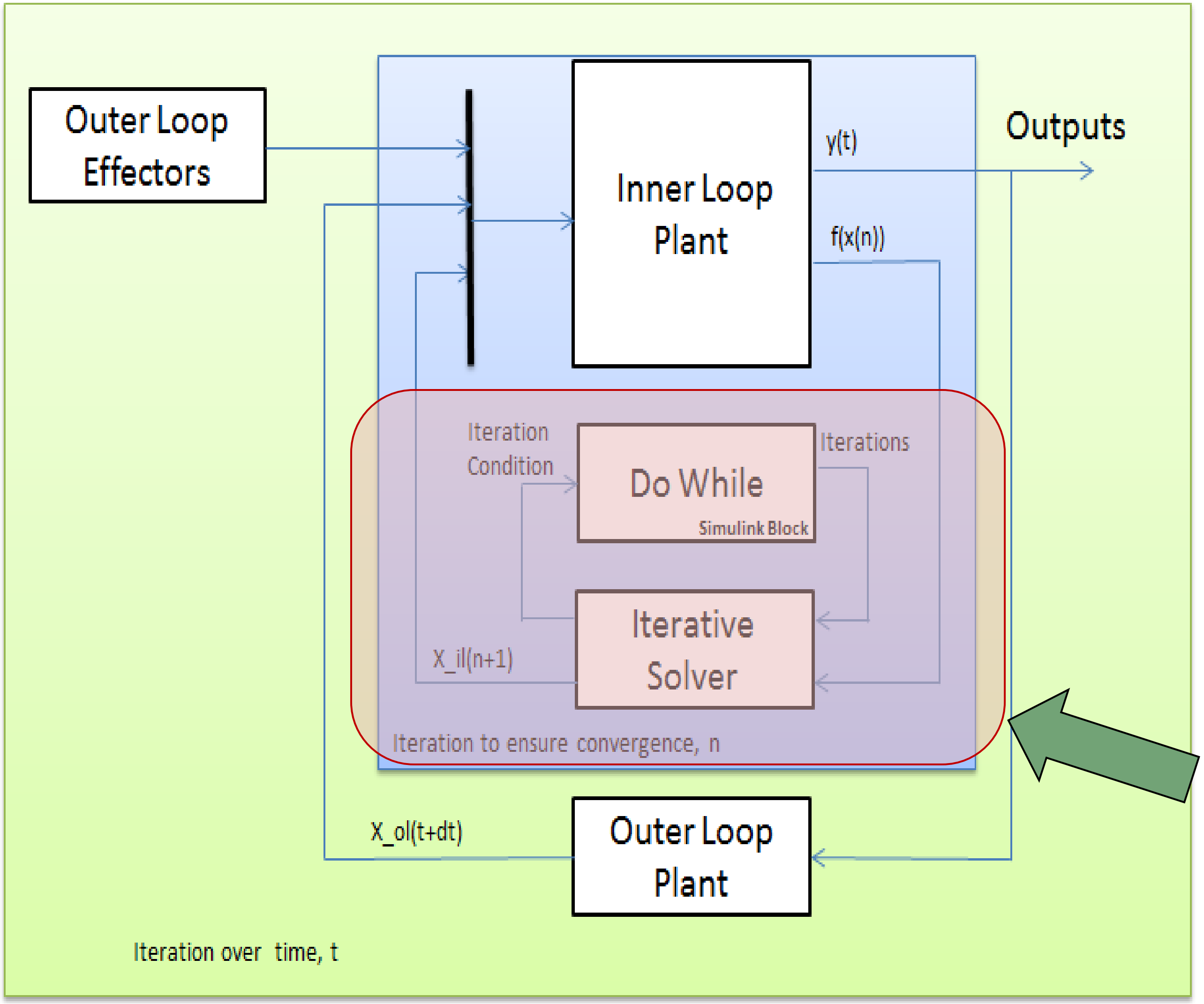


Dynamic Gas Turbine Example: Inner Loop Plant

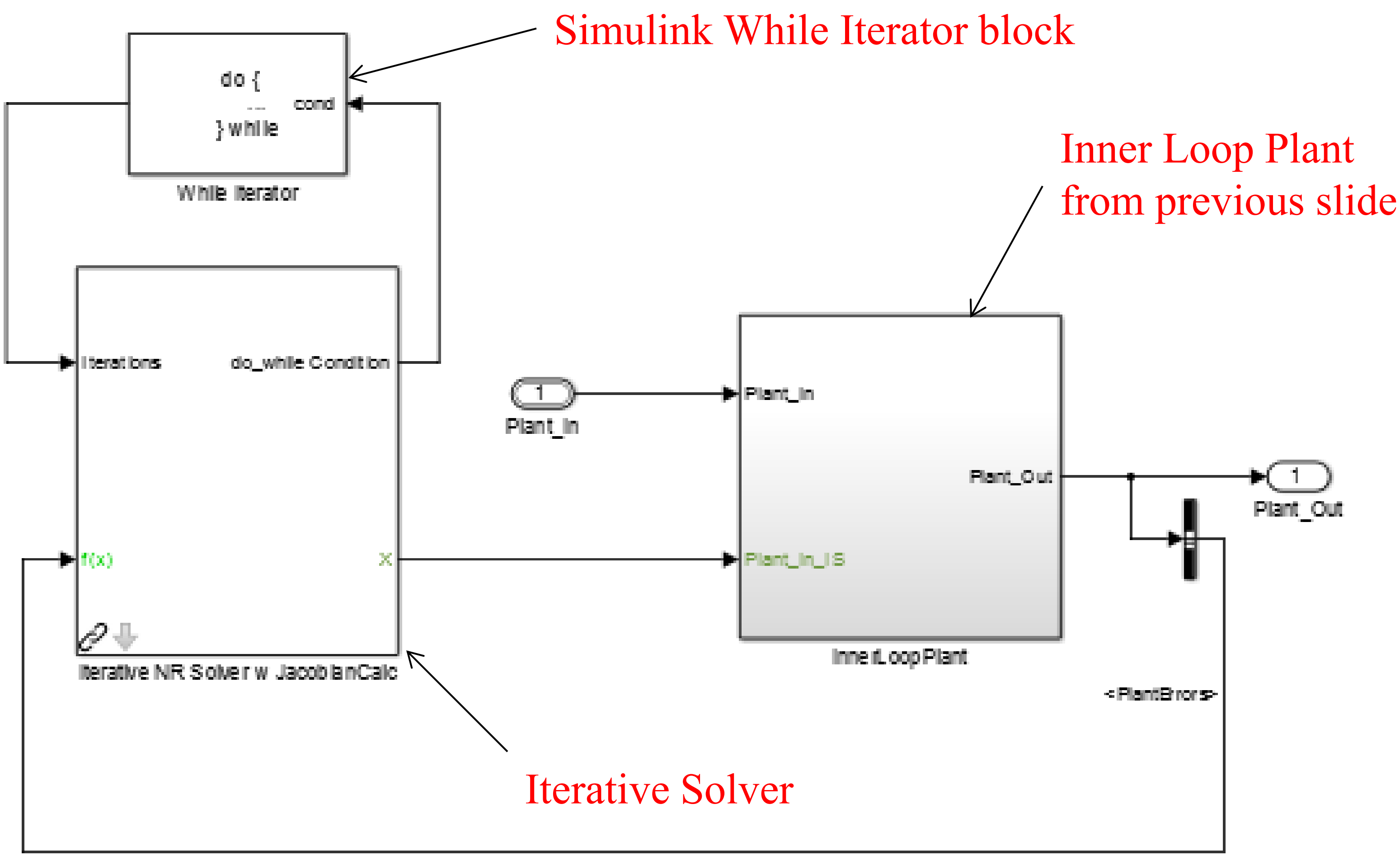


Turbojet plant model architecture made simple by T-MATS vectored I/O and block labeling

Dynamic Gas Turbine Example: Creating the Solver

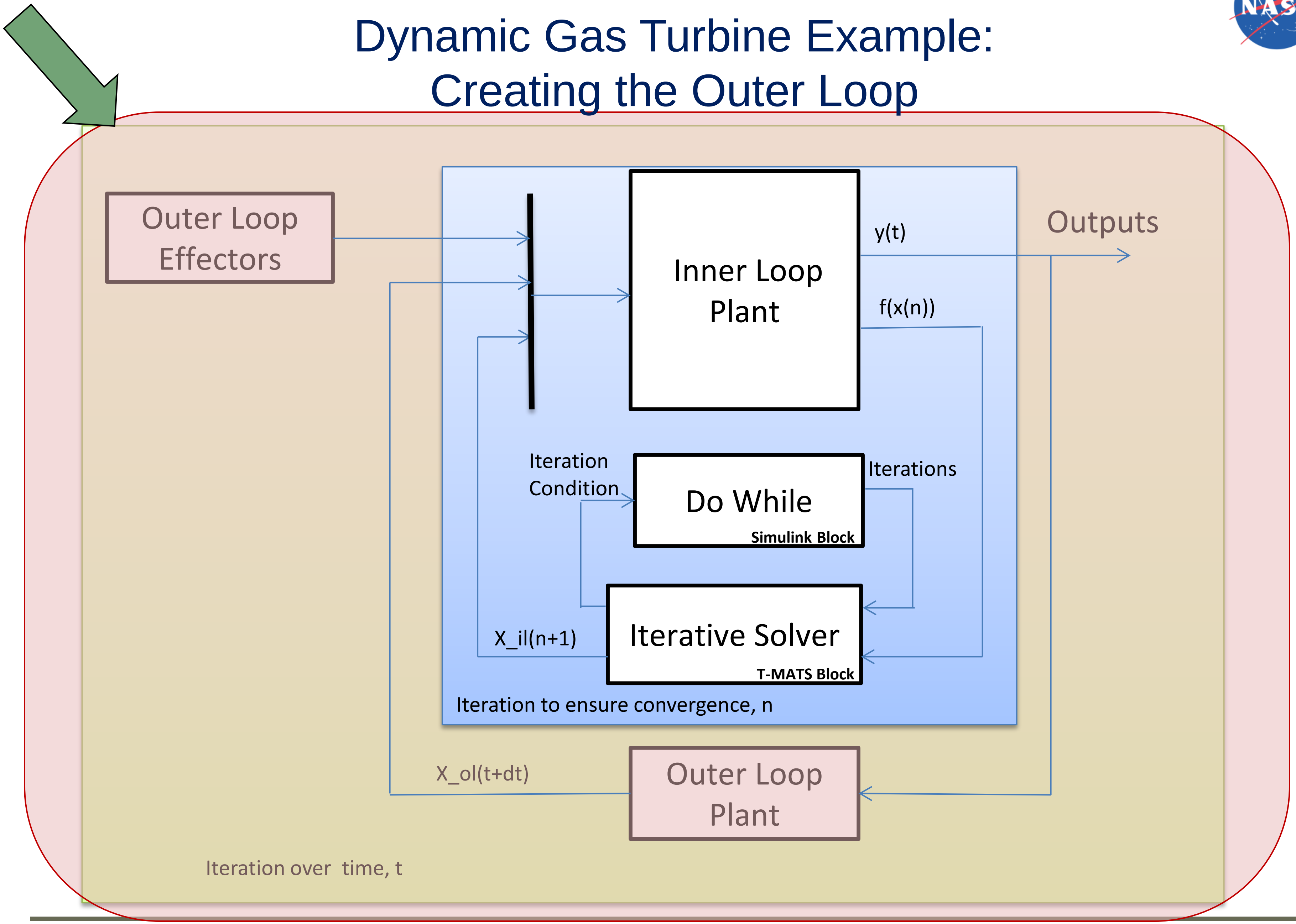


Dynamic Gas Turbine Example: Solver

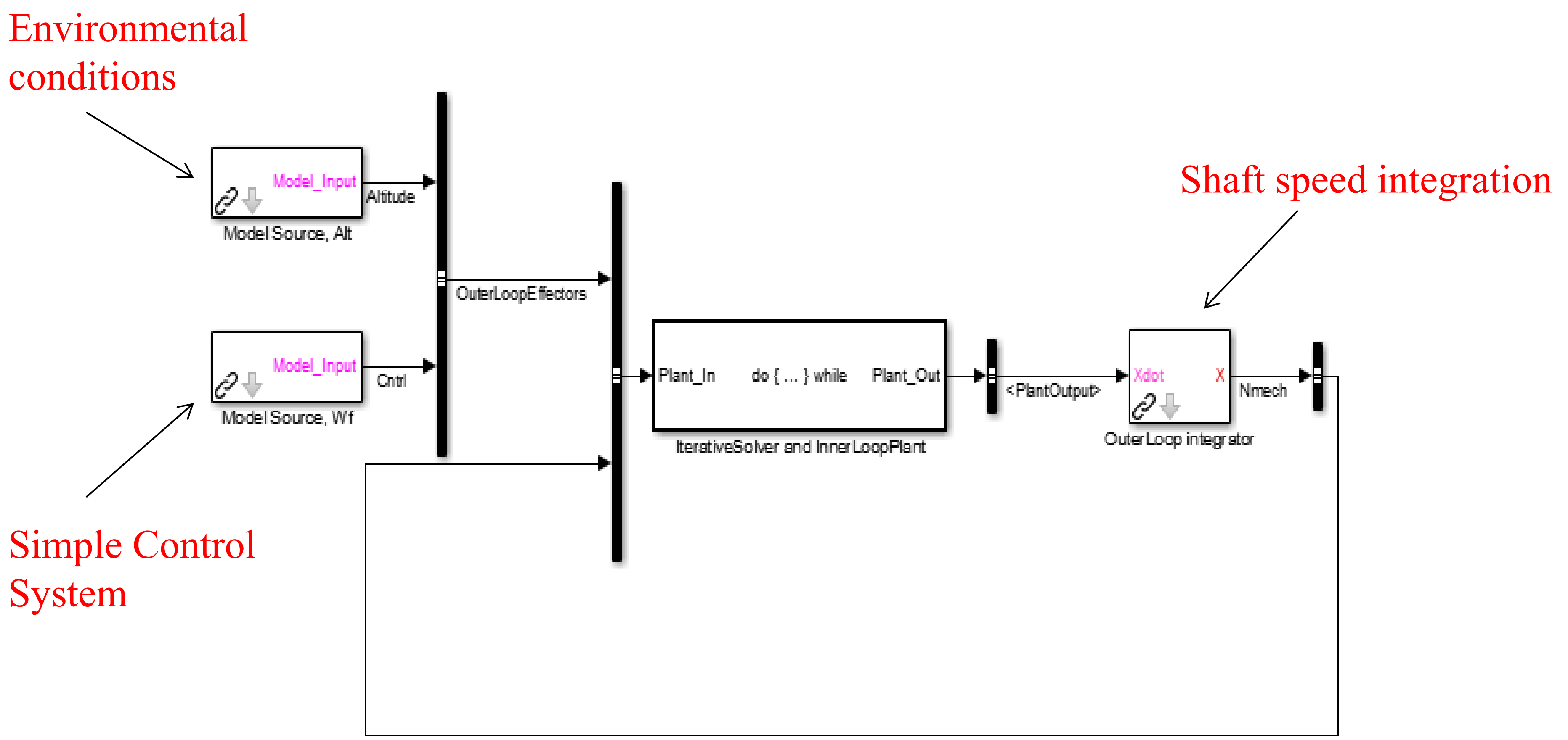


Plant flow errors driven to zero by iterative solver block in parallel with While Iterator

Dynamic Gas Turbine Example: Creating the Outer Loop



Dynamic Gas Turbine Example: Outer Loop Plant



Shaft integrator and other Outer Loop effectors added to create full system simulation

Verification and Release

- Verification was performed by matching T-MATS simulation data with other established simulations.
  - Models chosen for verification
    - NPSS steady-state turbojet model
    - C-MAPSS – High bypass turbofan engine model
  - In all cases differences in simulation performance were within acceptable limits.

- Expected Release: Q4,2013 or Q1,2014.
  - Pre-built examples will include:
    - Newton-Raphson equation solver
    - Steady state turbojet simulation
    - Dynamic turbojet simulation

Conclusions

- T-MATS offers a comprehensive thermodynamic simulation system
  - Thermodynamic system modeling framework
  - Automated system “convergence”
  - Advanced turbo-machinery modeling capability
  - Fast controller creation block set

Future Work

- Increase thermodynamic modeling capability
  - Introduce Cantera to T-MATS
    - “Cantera is a suite of object-oriented software tools for problems involving chemical kinetics, thermodynamics, and/or transport processes”
    - Open source
    - Increases thermodynamic modeling capability to include:
      - **Non-fuel specific gas turbine modeling**
      - **Fuel cells**
      - **Combustion**
      - **Chemical Equilibriums**

$$O + CH \Leftrightarrow H + CO$$